THE PROBLEM OF SCALE IN BIOINDICATION OF SOIL CONTAMINATION

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Abstract

Soil bioindication studies have often shown that species of different size groups show reactions to contaminants that were not expected on the basis of laboratory data. This phenomenon may be explained by the hierarchical organization of soil ecosystems in which different scales of time and space are involved. The lowest level is represented by ecosystems of unicellular and tiny multicellular organisms inhabiting or living in association with water films in soil pores and litter cavities. At the intermediate level there are ecosystems of small multicellular organisms dwelling in soil pores and litter cavities as a whole. Large multicellular organisms use the soil as a whole and they live in the soil ecosystem of the highest level. We prefer the latter organisms as bioindicators because they live in the same time-space scale as we. An early warning system for ecotoxicological effects can, however, not be elaborated on the basis of a single size group. A bioindicator system for soil pollution has to include organisms from differently-sized ecosystems and so take the problem of scale into account.

1. Introduction

A major difficulty associated with the interpretation of any bioindication or ecotoxicological study is that differently-sized species show different responses to toxicant exposure, in experiments and in the field. In addition, the reaction to toxicant exposure in the field may be quite different from the reaction shown in laboratory experiments [1, 2, 3]. These problems have to be solved before ecotoxicological risk

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assessment methods based on soil organism studies can be applied successfully [4, 5].

The mechanisms underlying the ecotoxicity of soil pollutants have been discussed previously [5, 6, 7]. One of the main factors is the sensitivity of a species to a toxicant. A second factor is the physiological state of the species observed, while a third important factor is the time-space dimension of the ecosystem in which the species lives, including the interactions with other organisms. This paper will concentrate on problems of scale in time and space, and the consequences of scale for the population responses towards the emission of toxicants into the soil environment. I will argue that it is necessary to include spatial and temporal dimensions in any risk assessment system that aims to predict the real risk of soil contamination.

2. Size relationships in soil

Ghilarov [8] has shown that there is a clear negative correlation between the abundance of soil animals and the body size of the species. Edwards [9] underlined that there are different biotic relationships between soil animals of different size groups. Ceitlin and Byzova [10] observed that different size groups of soil animals have a similar biomass, on a logarithmic scale. It can thus be supposed that species of the same size group form a network of trophic and other interactions on their own, relatively independent of other size groups. Tight nutrient cycles have to be maintained within such systems [11], while interactions with other systems take place by means of organic matter fluxes and oxygen produced by higher plants and algae. The systems of small dimensions develop inside the systems of larger size.

Ghilarov [12] has also underlined that the soil environment provides a habitat for three groups of soil organisms: water film dwellers (protozoans, rotifers, tardigrades), soil pore dwellers (microarthropods and other microfauna species), and real soil dwellers (earthworms and macroarthropods). Each group exploits a food resource independent from the other groups: the first group feeds on bacteria and algae, or animals of the same size, the second group feeds on fungi, or animals of the same size, and the third one feeds on plant tissue (living or dead), or animals of the same size. During its development, an individual animal can, however, move from one group to another. For example, the young stages of the lithobiid *Monotarsobius curtipes* feed on springtails, since they are in the same size group, but the adult animals do not use springtails anymore [13]. The same phenomenon is known for spiders.

Large soil animals consume the ecosystems of smaller dimensions as a whole, and then use them as an essential part of their metabolism. Earthworms, diplopods, isopods, larvae and imagoes of insects consume

soil, litter and plant roots including the bacteria-algae-Protozoa ecosystems developed on them. These ecosystems undergo further development in the guts of earthworms or macroarthropods and supply saprophageous animals with essential amino acids, phosphorus, and vitamins [14, 15]. Soil and litter can be considered as sources of substrates, organic matter and nutrients for the ecosystems present in animal guts. In termites or ruminants, the gut ecosystems have become completely independent from the external environment and are connected with it only through the materials consumed by the animal.

In view of the considerations given above, one may distinguish in soil three relatively closed and independent ecosystems with different dimensions in space-time. The first ecosystem is the **bacteria-algae-Protozoa** ecosystem, consisting of unicellular organisms as well as some multicellular organisms such as tardigrades, rotifers, bacterivorous mites, springtails, and nematodes. These ecosystems have a size of a few mm to some cm, and a volume of some cubic cm. They are isolated in water fims of soil cavities or at root and litter surfaces. The ecological time of these ecosystems (the time of developing through one successional sequence) is in the order of days to months; biological turnover time (the time it takes for nutrient fluxes to replace nutrient stores) varies from a day to a week. During succession, the trophic structure of the system develops and populations of organisms at higher trophic levels appear. The predator component of this ecosystem is equivalent to the functional group in Moore *et al.* [16]

The second ecosystem is the **fungi-microarthropod** ecosystem, consisting of small multicellular organisms, including mites, springtails, nematodes, enchytraeids, and juvenile stages of large soil animals. These ecosystems are isolated in soil pores and cavities in the litter layer. They have a size varying from some cm to a few m, and are often limited by the rhizosphere volume of separate plants. Ecological time varies from a week to some months, while biological turnover time is in the order of days to months. The league concept of Faber [17] is the consumer component of this ecosystem.

The third ecosystem is the **earthworm-plant** ecosystem, consisting of large multicellular organisms. Its borders coincide with those of a plant community above ground. Ecological time varies from some years to decades, while biological turnover takes some months or more, up to some years.

An artist impression of the three ecosystems, including information on size and time relationships, is given in Fig. 1. It is important to realize that the ecosystems of lower levels are nested in the ecosystems of higher levels. A mosaic or patchy distribution of Protozoa and microarthropods is a reflection of the spatial distribution of small-scale ecosystems, and does not relate to the patchiness of the large-scale ecosystem in which it is nested.

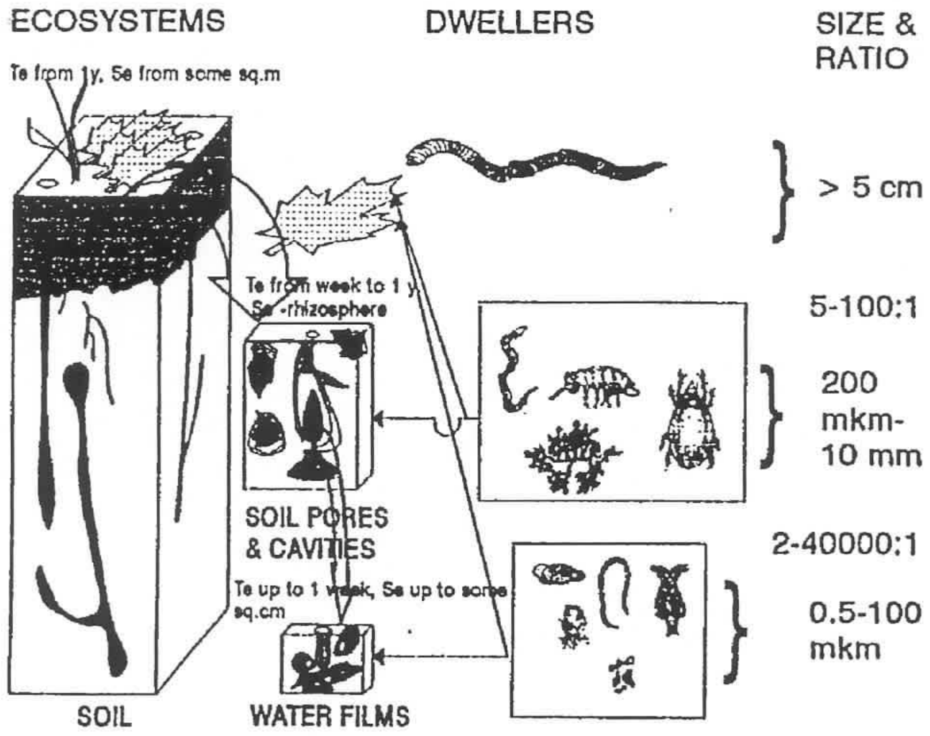

Figure 1. The proposed hierarchical concept of soil ecosystems, showing how the bacteria-algae-Protozoa ecosystem is nested in the fungi-microarthropod ecosystem, which in turn is nested in the earthworm-plant ecosystem. Te = ecological time (relating to succession), Se = ecosystem size.

Is it legitimate to consider these systems of different dimensions as separate ecosystems? They are connected with each other by means of energy fluxes and oxygen produced by plants and algae (although plants and algae belong to different systems). In the sense of Tansley [18] the three systems described here are to be considered as real ecosystems. The term "subsystem" is not convenient in this context, because Swift and Anderson [19] have used it already to describe the trophic structure of ecosystems; they distinguished "plant subsystem", "grazing subsystem", and "decomposer subsystem".

3. Consequences for bioindication and ecotoxicology

In a recent review, Eijsackers [6] has discussed the problem of scale in the context of the ecotoxicology of soil organisms. He paid attention to the fluctuations in environmental conditions, which have different consequences for organisms of different sizes. We may ask the question,

however, is it really necessary to define ecosystems of different scales? Are there any qualitative differences between the ecological processes in ecosystems of different scales? Some examples from bioindication and radioecological studies demonstrate that this is indeed the case.

In a field study on the influence of ^{90}Sr on soil Protozoa [1] it was found that populations of Protozoa, which are the most tolerant organisms towards ionizing radiation, were affected to a greater extent than populations of microarthropods, which are actually more sensitive [3, 20]. This is demonstrated in Fig. 2, showing data on soil animal populations affected by radioactive contamination in Southern Ural. In another study, conducted in the surroundings of the Chernobyl nuclear power plant after the accident in 1986 [2], microarthropod populations responded more obvious to radioactive contamination than earthworm populations, see Fig. 3. Similar responses were revealed in field studies with experimentally manipulated radioactive radiation [21]. It appears that radiation doses in small spaces (water films, soil pores) are much higher than expected on the basis of the measured (bulk) radioactivity of a soil.

The presence or absence of a single species of a tiny animal has a neglible effect on the soil as a whole, however, changes in mesofauna communities following application of pesticides may lead to changes in the decomposition of plant residues [22, 23]. Differences in the species composition of large animals may lead to marked changes in soil and in biogeochemical processes [24, 25]. The appearance or disappearance of microarthropods usually remains unnoticed, except for some parasites or

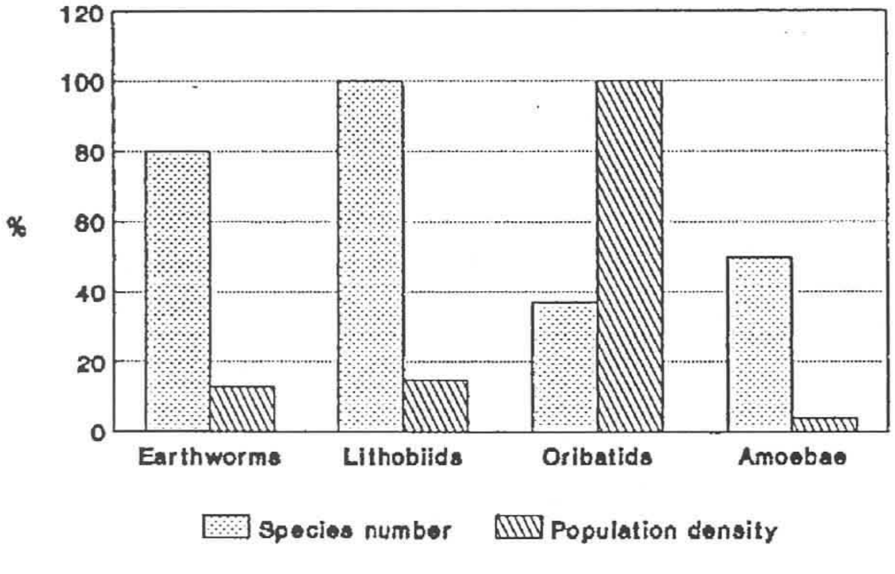

Figure 2. Changes (in % of the initial level) in populations of soil invertebrates of different size groups, affected by ^{90}Sr contamination in Southern Ural [1, 3, 20].

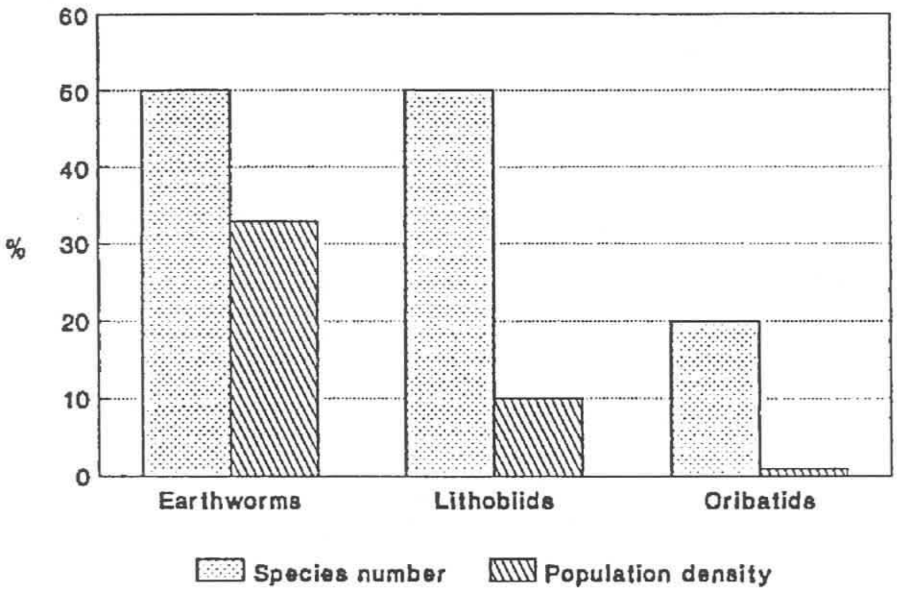

Figure 3. Changes (in % of the initial level) in populations of soil invertebrates of different size groups, affected by radioactive contamination at Chernobyl [2].

hosts of animal or plant diseases. Consequently, the role of a large animal in the biological turnover of a community is equivalent to the role of a group of small animals [11]; in ecosystems of their own dimensions, however, small species play the same role as large species in their ecosystems. As a consequence of the size-selective effects of soil ecosystems, the greatest number of soil species is known for the size group 5-10 mm, and the number of species declines sharply for smaller or larger groups [26].

An important consideration when interpreting bioindication data is that small animal species can specialize on particular food species. Different species of springtails were able to select a particular microfungus to feed upon, and the preference was influenced by heavy metal contamination of the substrate on which the fungi were growing [27, 28]. It is obvious that protozoans, tardigrades and rotifers, within the dimensions of their ecosystems, must be capable of selecting prey items that we cannot identify as separate species.

One of the reasons why earthworms are absent from plots contaminated by heavy metals is that contamination alters the composition of the microbial community [29]. In other words, the disappearance of an ecosystem at a low level may lead to the disappearance of an ecosystem at the highest level.

4. Bioindication on the basis of the hierarchical system

Sukachev, in his "biogeocoenosis" [30] proposes a hierarchical system of ecosystems of at least three size levels (not in the sense of O'Neill *et al.* [31]). These systems are more or less closed, connected to each other only through fluxes of organic matter, without trophic interactions between them. What is the relevance in elaborating a bioindication system for the assessment of soil pollution and other human influences? Some consequences of the considerations given above may be listed as follows.

1. The influence of the same factor in soil ecosystems of different dimensions is qualitatively different. An ecosystem of a certain scale cannot not be used as a model for ecosystems of other dimensions, and the extrapolation of data between systems of different scales may be incorrect. This has to be taken into account in any bioindication study.

2. Organisms that live in an ecosystem of the first level will reflect toxicant impacts already on a short term. This is a result of the short life-cycles of most of the organisms, a high rate of pollution-induced natural selection in the populations, and a quick succession, resulting in a relatively short exposure time for an individual ecosystem. Another reason why small organisms reflect toxicant impacts on a short term is related to the high degree of patchiness of the toxicant's distribution at the microscale level. In addition, small organisms take up toxicants mainly from the water phase, where it is present in a soluble and in highly bioavailable form.

3. Organisms inhabiting ecosystems of the second scale level reflect the mid-term impacts of a toxicant. This is the result of a relatively long life-cycle of most of the species (compared to the organisms in the first level), a lower genetic flexibility of the populations, and a relatively long exposure time of the ecosystems. There are physico-chemical barriers, such as organic matter and microorganisms developing on it, that hamper the uptake of toxicants by organisms.

4. Large organisms are indicators of long-term effects of toxicants in soil, due to long life-cycles, a role in soil forming processes, and an influence on soil organisms living in lower level ecosystems. In turn, effects on ecosystems of lower scale will often influence organisms at the higher scale later.

Considering the above listed arguments, we have to develop a bioindication and ecotoxicological system that includes organisms from soil ecosystems of different dimensions. A conceptual scheme for such a system is proposed in Fig. 4. For practical purposes, concrete organisms and procedures have to be selected. Many of the organisms and procedures have been considered before, and the selection of methods for field bioindication does not seem to present many difficulties [3, 32]. A coherent set of organisms for risk assessment and early warning of the

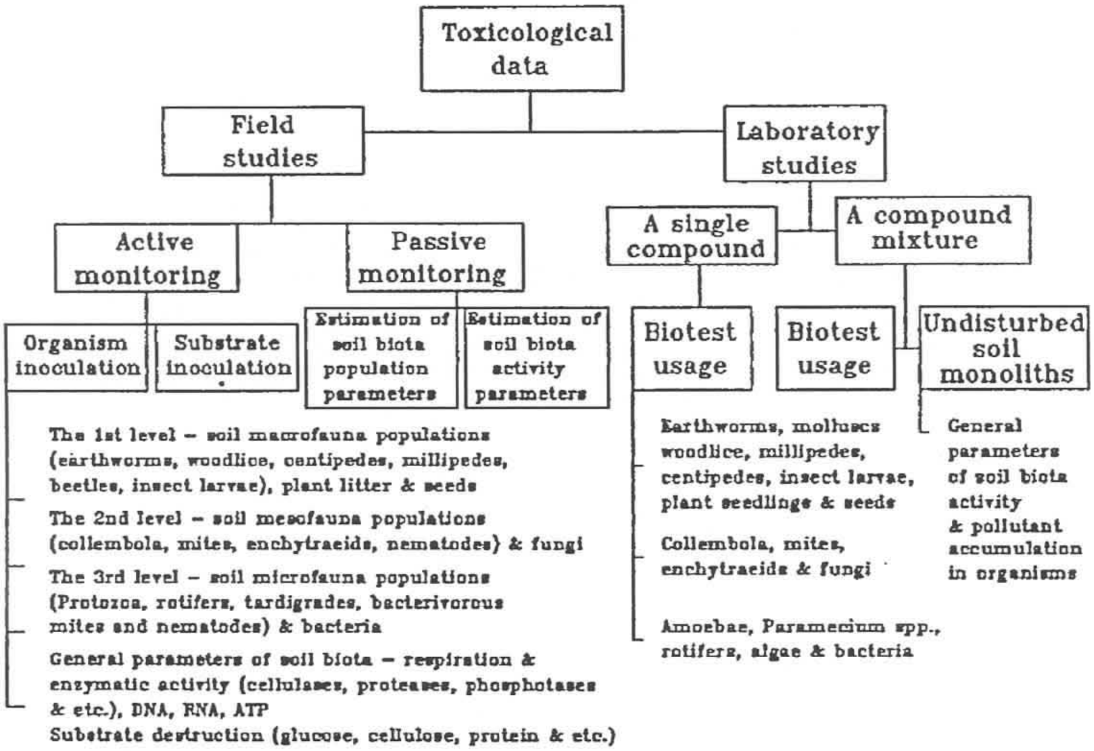

Figure 4. A conceptual scheme for a soil bioindication system

ecotoxicity of different compounds and their mixtures is required. At the moment, only *Eisenia foetida* as the model organism and decomposition as the model proces are being considered for the assessment of ecotoxicity of new compounds [33].

To develop risk assessment methods for soil contamination, there is a continuing search for new organisms and new procedures [34, 35], however, most of them are for large animals. In my opinion, it is more important to elaborate standard procedures for reference organisms of the lower level ecosystems. Enchytraeids, springtails, nematodes and rotifers deserve attention due to ease of cultivation [34, 35, 36] and ease of exposure methods. There is also a method for predicting effects of toxicants in mixtures, the "undisturbed monolith method", that is used for the assessment of toxicant mixtures [37, 38].

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